New bathymetry model of Lake Vostok from airborne gravity data

I. Filina,[1] D. Blankenship,[1] V. Lukin,[2] V. Masolov,[3] and M. Sen[1]

[1]The Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, 10110 Burnet Rd., Bldg. 196, Austin, TX 78758, USA (irina@ig.utexas.edu, and blank@ig.utexas.edu)
[2]Russian Antarctic Expedition, 38 Bering Str., Saint Petersburg,199397, Russia (lukin@aari.nw.ru)
[3]Polar Marine Geological Research Expedition, 24 Pobeda Str., Saint Petersburg, Lomonosov, 188512, Russia (masolov@polarex.spb.ru)

Summary The new 3D bathymetry model for the largest known subglacial lake in Antarctica – Lake Vostok – was developed via inversion of airborne gravity data, constrained by 60 seismic soundings. The presented model consists of water and unconsolidated sediment layers overlying the host rock with density of 2.55 g/cc, which was inferred from prior 2D modeling. The layer of unconsolidated sediment incorporated into the model has an assumed density of 1.85 g/cc. This layer was originally interpreted from seismic data to be 50 m thick in the northern part of the lake, while a revised interpretation of seismic data suggests that this layer is 350 -380 m thick. The revised thickness makes the unconsolidated sediments in Lake Vostok a significant source of gravity anomaly (up to 8 mGal in the northern basin). Previous gravity models (based on the same gravity dataset) are compared and contrasted with our new one. Our presented 3D bathymetry model of Lake Vostok corresponds better with seismic data (RMS of 125 m) than two previous models.

Citation: Filina, I., D. Blankenship, V. Lukin, V. Masolov, and M. Sen (2007), The bathymetry of Lake Vostok from airborne gravity data: A new model based on the same dataset: *in* Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R, Raymond et al., USGS Open-File-Report 2007-1047, Extended Abstract 178, 4 p.

Introduction

The largest known subglacial lake – Lake Vostok – is located beneath Russian Station Vostok in East Antarctica. This large, fresh-water lake, covered with 4 km of ice, attracts much attention from the scientific community due to its uniqueness and possibly life-supporting environment. The north-plunging lake ceiling causes the difference in the temperature/pressure at the bottom of the ice sheet, over different parts of the lake (Siegert, 2005; Studinger et al., 2003). Those differences trigger melting at the ice-water interface in the northern part of the lake but freezing of the lake water onto the bottom of the ice sheet in the southern part of the lake. Such a distribution of melting/freezing patterns, in turn, is believed to be responsible for generating water circulation within the lake (Siegert, 2005). All of these internal processes within Lake Vostok are subject for numerical modeling. The key 'a priori' information for such modeling is the 3D geometry of the lake, which infers both spatial and depth distribution of water as well as unconsolidated sediments at the bottom of the lake. The lake's coast line is well mapped by radar sounding data (Figure 1), providing the spatial constrains for both water and sedimentary layers.

To date, two 3D models of the Lake Vostok bathymetry are known (Roy et al., 2005; Studinger et al., 2004). Both of them are based on airborne geophysical data, collected by the University of Texas Institute for Geophysics (UTIG) during 2000-2001 field season (Richter et al., 2001; Studinger et al., 2003; Holt et al., 2006), constrained with seismic data available at the time. The purpose of this paper is to present a new model of lake's bathymetry based on 3D inversion of the same gravity dataset constrained with seismic soundings available to date (Figure 1), as well as to compare and contrast the new model with previous models.

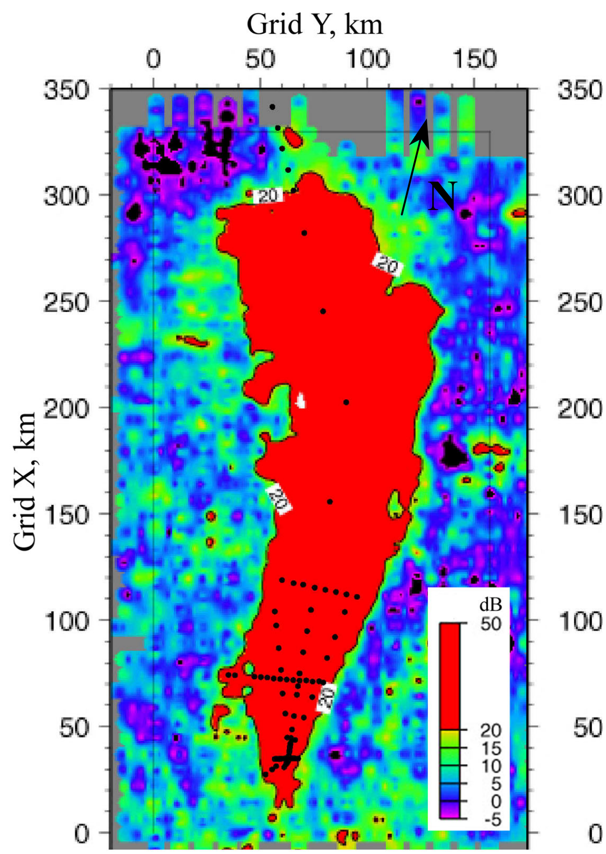

Figure 1. The radar sounding bed echo strength map of Lake Vostok area (Sasha Carter – personal communication); the lake is assumed to be the region of high echo strength. Black dots indicate seismic soundings.

Available data

The airborne geophysical data were collected on a regular grid with 7.5 km spaced east-west lines and 11.25 and 22.5 km spaced north-south tie lines. The flight elevation was 3.96 km above mean sea level (msl). The reduction of the gravity data used in Roy at al. (2005) and this study was performed at UTIG (Holt et al., 2006) with a reported RMS of the differences at the crossover points for the gravity grid after leveling of 1.2 mGal. Studinger et al. (2004) uses the reduction algorithm based on Childers et al. (1999) and reports the standard deviation of the adjusted crossover error of 2.7 mGal.

There are sparse seismic soundings over the lake (Masolov et al., 1999; Item CEP4c, 2002; Masolov et al., 2006), mostly located in the southern part of the lake (black dots in Figure 1). Seismic data suggests the lake is deeper in the southern part. The maximal water thickness recorded by seismic soundings is 1200 m at southern part of the lake (Item CEP4c, 2002; Masolov et al., 2006); the water thickness decreases up to 250 m to the north of the lake. Also, the seismic data beneath Vostok station reveal the presence of a relatively small (about 5 km across and 690 m deep) basin filled with 350 m of sediment (Masolov, 1999).

The presence of unconsolidated sediments at the bottom of Lake Vostok was originally reported based on interpretation of seismic data (Masolov et al., 1999; Item CEP 4c, 2002). This layer was believed to be up to 350 m in the southern part beneath Vostok Station and becoming thinner up to 50 m in the northern part of the lake. However, the most recent publication (Masolov et al., 2006) suggests that the lake's water overlies the acoustic basement, inferring that there is no sedimentary layer at the bottom of Lake Vostok. The presence of sediments is confirmed from seismic data (Filina et al., 2007; Filina et al., 2006), revealing a existence of at least 200 m of unconsolidated sediments in the southern part of the lake and 350 -380 m in the northern basin.

Previous 3D bathymetry models

The first 3D bathymetry model (Roy et al., 2005 (submitted in 2003)) was developed for both water and sediment layers, showing the maximal water depth of 1550 m in the northern basin and sediment thickness of 300 m. In Roy et al. model, the ice and water were considered to be one layer due to their similar densities. The different densities of the host rocks were used (2.6 g/cc for the lake's cavity area, 2.8 g/cc east of the lake) to represent the presence of the thrust fault suggested by Studinger et al. (2003). Roy et al. (2005) used the sediment density of 2.0 g/cc. They chose the regional trend, required to calculate the residual anomaly before inversion, to be linear. The inversion was performed using Very Fast Simulating Annealing algorithm. This model has significant discrepancy with seismic data, as well as spatial divergence with coastline obtained from radar sounding data.

Another model (Studinger et al., 2004) was composed for the water layer only. Since the sedimentary layer was believed to be thin, it was ignored during modeling. This model shows the maximal water thickness in the lake of 800 m in the southern basin and about 450 m in the northern basin. Their comparison with seismic data at 19 points (RMS of 250 m) shows better agreement than the model of Roy at al., 2005. Studinger et al. (2004) model was developed for a density of the host rock of 2.67 g/cc. A regional trend of the second order was calculated based on "the misfit between the regional bedrock topography inverted from gravity and the bedrock topography from radar data" (Studinger et al., 2004).

Both of these models still have some discrepancy between seismic and gravity derived water thickness. In the southern basin, the maximal water thickness recorded by seismic data is 1200 m, while in the northern basin the water layer does not exceed 250 m.

New 3D model

All available airborne data were interpolated into a regular grid with 5 km cell, which is smaller than an estimated resolution of gravity data for the survey parameters used (Childers et al., 1999; Holt et al., 2006). The model was composed of water and sediment layers overlying bedrock with a density of 2.55 g/cc. The density of sediments was chosen to be 1.85 g/cc. The forward problem was solved based on the equation of Parker (1973).

Before the inversion, the gravity effects of al known sources (ice layer (ice density of 0.92 g/cc) and rocks above msl) were calculated and removed from observed Free-Air anomaly. This reduced anomaly increases rapidly over the lake by about 70 mGal — from the western edge to the eastern edge of the lake basin. The regional trend, representing the gravity effect of deeper geological structures, should be removed before the modeling. This trend was found for several 2D profiles spaced by 50 km by cubic spline interpolation and later interpolated over entire lake region. The inversion was performed by a conjugate gradient method for both water and sediments layers.

The new bathymetry model of Lake Vostok (Figure 2) has the maximal water thickness of 1100 m in the southern basin, showing very good correlation with seismic data. The RMS of difference between water thicknesses derived from seismic data and gravity modeling is 125 m. In the northern basin the water depth is 230 m. The thickness of inverted sedimentary layer is up to 250 m in the southern basin and 350 m in the northern one, which is also consistent with seismic data.

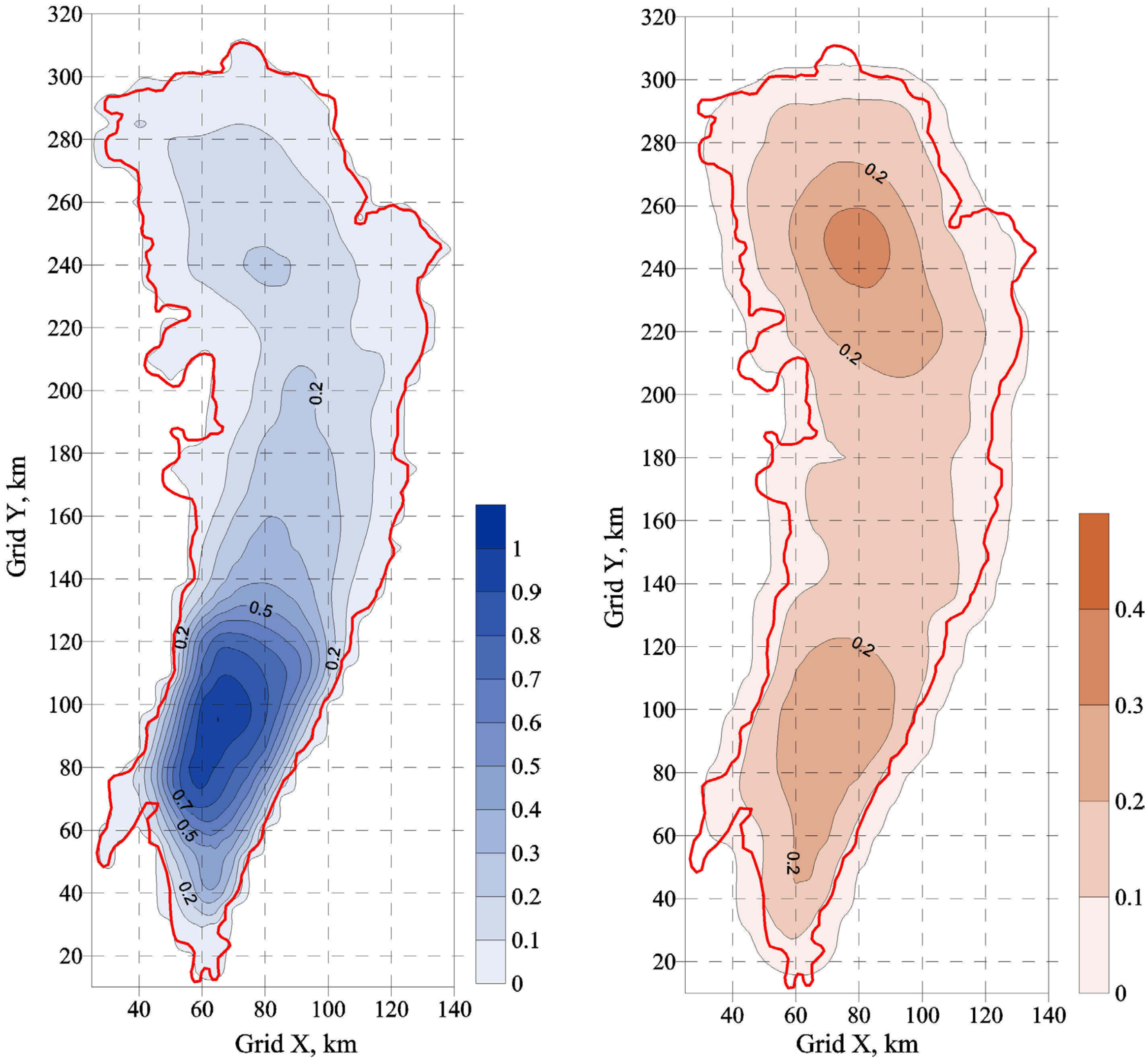

Figure 2. The preliminary results of inversion: (a) the water thickness in km; contour interval (CI) is 0.1 km; red line shows the lake's coastline from radar data; (b) the sediments thickness (km); CI is 0.1 km;

Discussion

The gravity anomaly is a function of the anomalous mass geometry and its density contrast with the host rock. The proposed model for Lake Vostok consists of water and unconsolidated sediments layers overlying the host rock. The density of water is know (1 g/cc), while density of unconsolidated sediments and the host rocks should be properly chosen and fixed during inversion. In this study sediments at the bottom of the lake were chosen to have density of 1.85 g/cc, which is consistent value for water-filled unconsolidated sediments.

Previous 2D gravity modeling of Lake Vostok suggests the best agreement between water thickness derived from seismic soundings and from gravity inversion of 2.55 g/cc (Filina et al., 2006). The chosen density of 2.55 g/cc, typical for consolidated sedimentary rocks, is also consistent with the model of Studinger et al. (2003), where the presence of a sedimentary basin beneath Lake Vostok was suggested. If the density of 2.67 g/cc is used during modeling, the lake's depth decreases by about 200 m. This is one of the possible explanations for lake appearing to be shallower (up to 800 m) in Studinger et al. (2004) model than it actually is (1200 m based on seismic), since Studinger et al. (2004) utilizes density of 2.67 g/cc for the host rock.

Another reason for the discrepancy in water thickness derived from the Studinger et al. (2004) gravity inversion and seismic soundings is the omission of a sedimentary layer. Based on the seismic soundings, the layer of unconsolidated sediments in the northern basin appears to be thicker than the water layer (350- 380 m of sediments vs. 250 m of water). Those sediments are responsible for a gravity effect up to 8 mGal, which exceeds the accuracy of the gravity data by several times. That is why the sedimentary layer can not be ignored during modeling.

The model of Roy et al. (2005) includes the presence of the sediments at the bottom of the lake, although its thickness was constrained based on the distribution reported in Masolov et al. (1999). The most possible reason for the disagreement of inverted water thickness with seismic data in Roy et al. (2003) model is the utilizing of linear regional trend. This also resulted in a spatial discrepancy with the lake's coastline.

Both of the previous models and the presented new one do not represent the small basin beneath Vostok station, which is about 5 km wide. The reason for that is that the dimension of this basin is smaller than the resolution of this airborne gravity dataset (Childers et al., 1999; Holt et al., 2006), so it does not appear in the gravity derived models.

Summary

The new 3D bathymetry model of subglacial Lake Vostok, East Antarctica was developed. This model is based in the inversion of airborne gravity data, constrained by available to date seismic soundings. The major difference between this model and two previous models is that the value of 2.55 g/cc for the host rock density was utilized based on the results of prior 2D modeling. This model also incorporates a new interpretation of the seismic data, suggesting that sedimentary layer is 350 -380 m thick in the northern basin of the lake in contrast to previously reported 50 m. This layer is responsible for the gravity anomaly up to 8 mGal, which is significantly higher than the accuracy of a dataset. All of these lead to better correlation of the presented model with available seismic data (RMS of the differences in water thickness is 125 m).

Acknowledgments. The authors thank the Jackson School of Geosciences for the financial support. Theresa Diehl of the UTIG is thanked for help with manuscript preparation and valuable comments. Special thanks go to Svetlana Mironova and Valery Krivopishin for the great assistance and generous support during preparation of this paper.

References

Childers, V. A., R. E. Bell, and J. M. Brozena (1999), Airborne gravimetry: An investigation of filtering, Geophysics, 64(1), 61–69.

Filina, I., V. Lukin, V. Masolov, and D. Blankenship (2007), Unconsolidated sediments at the bottom of Lake Vostok from seismic data, in Antarctica: A keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R, Raymond et al., USGS Open-File-Report 2007-1047,Short Research Paper 031,5 p.; doi:10.3133/of2007-1047.srp031

Filina I., V. Lukin, V. Masolov, D.D. Blankenship (2006), Are there unconsolidated sediments at the bottom of Lake Vostok?, *2nd SCAR Open Science Conference "Antarctica in the Earth System"*, Hobart, Tasmania, July, 12 -14, 2006

Filina, I., D. Blankenship, L. Roy, M. Sen, T. Richter and J. Holt (2006), Inversion of airborne gravity data acquired over subglacial lakes in East Antarctica, "Antarctica - Contributions to Global Earth Sciences", Proceedings of the 9th ISAES, edited by Dieter Fütterer, Springer Publishing House, Berlin, p. 129 – 134

Holt, J. W., T. G. Richter, S. D. Kempf, D. L. Morse, and D. D. Blankenship (2006), Airborne gravity over Lake Vostok and adjacent highlands of East Antarctica, Geochemistry, Geophysics, Geosystems, 7, Q11,012, 10.1029/2005GC001177

Item CEP 4c (2002), Water sampling of the subglacial lake Vostok draft comprehensive environmental evaluation, XXV Antarctic Treaty Consultative Meeting, 10 – 20 September, Warsaw, Poland (www.ats.aq/25atcm/25atcmWP.htm)

Masolov, V., S. Popov, V. Lukin, A. Sheremetyev and A. Popkov (2006), Russian Geophysical Studies of Lake Vostok, Central East Antarctica, "Antarctica - Contributions to Global Earth Sciences", Proceedings of the 9th ISAES, edited by Dieter Fütterer, Springer Publishing House, Berlin, p. 135 – 140

Masolov, V. N., G. A. Kudryavtsev, A. N. Sheremetiev et al. (1999), Earth Science Studies in the Lake Vostok region: Existing data and proposals for future research, in Subglacial Lake Exploration—Workshop Report and Recommendations, Addendum, report, pp. 1 – 18, Cambridge Univ., U. K.

Parker, R. L. (1973), Rapid calculation of potential anomalies, Geophys. J. R. Astron. Soc., 31(4), 447– 455.

Richter, T. G., J. W. Holt, and D. D. Blankenship (2001), Airborne gravimetry over the Antarctic ice sheet, paper presented at the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada.

Roy, L., M. Sen, D. Blankenship, P. Stoffa, and T. Richter (2005), Inversion and uncertainty estimation of gravity data using simulated annealing: An application over Lake Vostok, East Antarctica. Geophysics, Vol. 70, Issue 1, pp. J1-J12

Siegert, M. (2005), Reviewing the origin of subglacial Lake Vostok and its sensitivity to ice sheet changes. Progress in Physical Geography 29, 2, 156-170

Studinger, M., R. E. Bell, and A. A. Tikku (2004), Estimating the depth and shape of subglacial Lake Vostok's water cavity from aerogravity data, Geophysical Research Letters, 31, L12401, doi:10.1029/2004GL019801.

Studinger, M., Bell, R.E., Karner, G.D., Tikku, A.A., Holt, J.W., Morse, D.L., Richter, T.G., Kempf, S.D., Peters, M.E., Blankenship, D.D., Sweeney, R.E. and Rystrom, V.L. (2003), Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica. Earth and Planetary Science Reviews, 205, 195-210.